# 10. PEGs, Packrats and Parser Combinators

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Thanks to Bryan Ford for his kind permission to reuse and adapt the slides of his POPL 2004 presentation on PEGs.
http://www.brynosaurus.com/

## Roadmap

- Domain Specific Languages
- Parsing Expression Grammars
- Packrat Parsers
- Parser Combinators

# Sources

> **Parsing Techniques — A Practical Guide**
>
> — Grune & Jacobs, Springer, 2008
>
> — *[Chapter 15.7 — Recognition Systems]*

> **"Parsing expression grammars: a recognition-based syntactic foundation"**
>
> — Ford, POPL 2004, doi:10.1145/964001.964011

> **"Packrat parsing: simple, powerful, lazy, linear time"**
>
> — Ford, ICFP 02, doi:10.1145/583852.581483

> **The Packrat Parsing and Parsing Expression Grammars Page:**
>
> — http://pdos.csail.mit.edu/~baford/packrat/

> **Dynamic Language Embedding With Homogeneous Tool Support**
>
> — Renggli, PhD thesis, 2010, http://scg.unibe.ch/bib/Reng10d

# Roadmap

- **Domain Specific Languages**
- Parsing Expression Grammars
- Packrat Parsers
- Parser Combinators

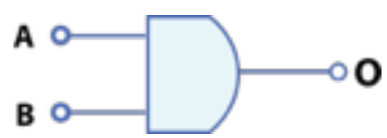
## Domain Specific Languages

> A DSL is a specialized language targeted to a particular problem domain
  —Not a GPL
  —May be *internal* or *external* to a host GPL
  —Examples: SQL, HTML, Makefiles

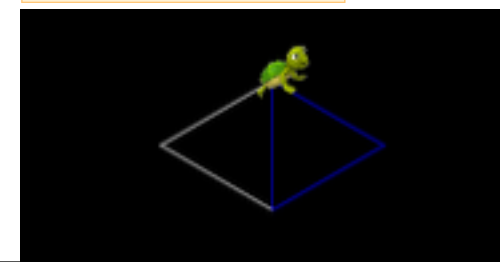
# External DSL's (Examples)

```
-- this is the entity
entity ANDGATE is
  port (
    A : in std_logic;
    B : in std_logic;
    O : out std_logic);
end entity ANDGATE;

-- this is the architecture
architecture RTL of ANDGATE is
begin
  O <= A and B;
end architecture RTL;
```




```
pencolor white
fd 100
rt 120
fd 100
rt 120
fd 100
rt 60
pencolor blue
fd 100
rt 120
fd 100
rt 120
fd 100
rt 60
```



# Internal DSLs

*A "Fluent Interface" is a DSL that hijacks the host syntax*

## Function sequencing

```
computer();
   processor();
      cores(2);
      i386();
   disk();
      size(150);
   disk();
      size(75);
      speed(7200);
      sata();
   end();
```

## Function nesting

```
computer(
   processor(
      cores(2),
      Processor.Type.i386),
   disk(
      size(150)),
   disk(
      size(75),
      speed(7200),
      Disk.Interface.SATA));
```

## Function chaining

```
computer()
   .processor()
      .cores(2)
      .i386()
      .end()
   .disk()
      .size(150)
      .end()
   .disk()
      .size(75)
      .speed(7200)
      .sata()
      .end()
   .end();
```

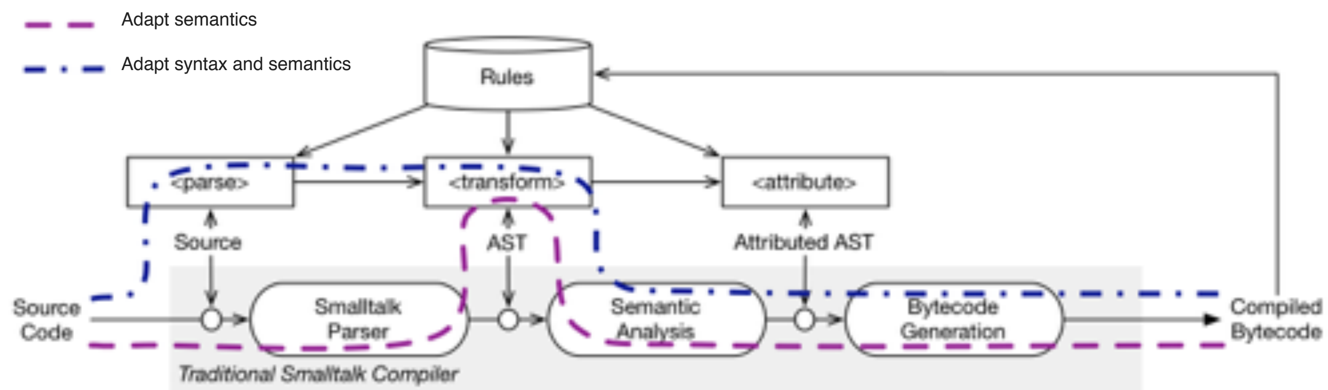
# Fluent Interfaces

> *Other approaches:*
> —Higher-order functions
> —Operator overloading
> —Macros
> —Meta-annotations
> —…

```
sizer.FromImage(i)
 .ReduceByPercent(x)
 .Pixalize()
 .ReduceByPercent(x)
 .OutputImageFormat(ImageFormat.Jpeg)
 .ToLocation(o)
 .Save();
```

# Embedded languages

An *embedded language* may adapt the syntax or semantics of the host language




*We will explore some techniques used to specify external and embedded DSLs*

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- > Domain Specific Languages
- > **Parsing Expression Grammars**
- > Packrat Parsers
- > Parser Combinators

## Recognition systems

"Why do we cling to a **generative** mechanism for the description of our languages, from which we then laboriously derive recognizers, when almost all we ever do is **recognizing** text? **Why don't we specify our languages directly by a recognizer**?"

Some people answer these two questions by "We shouldn't" and "We should", respectively.

*— Grune & Jacobs, 2008*

## Designing a Language Syntax

***Textbook Method***

1. Formalize syntax via context-free grammar
2. Write a parser generator (.*CC)  specification
3. Hack on grammar until "nearLALR(1)"
4. Use generated parser

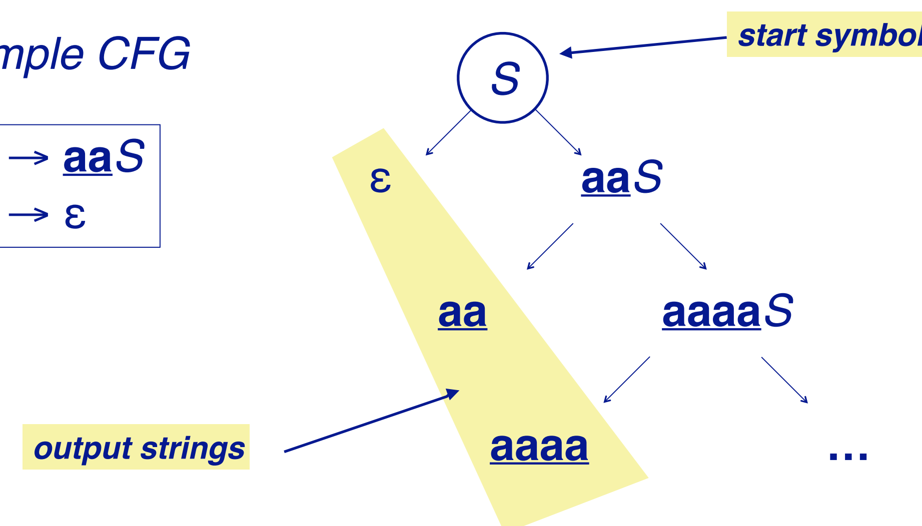
http://www.brynosaurus.com/pub/lang/peg-slides.pdf

## What exactly does a CFG describe?

***Short answer:*** a rule system to *generate* language strings

*Example CFG*

$S \rightarrow$ **aa**$S$
$S \rightarrow \varepsilon$




http://www.brynosaurus.com/pub/lang/peg-slides.pdf

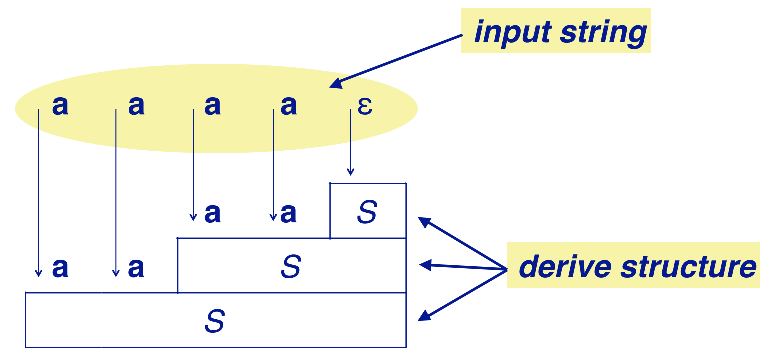
# What exactly do we *want* to describe?

***Proposed answer:*** a rule system to *recognize* language strings

*Parsing Expression Grammars* (PEGs) model
recursive descent parsing best practice

*Example PEG*

$S \leftarrow \underline{\mathbf{aa}}S \,/\, \varepsilon$



# Key benefits of PEGs

- Simplicity, formalism of CFGs
- Closer match to syntax practices
  - More expressive than deterministic CFGs (LL/LR)
  - Natural expressiveness:
    - *prioritized choice*
    - *syntactic predicates*
  - **Unlimited lookahead**, backtracking
- Linear time parsing for any PEG (!)

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

# Key assumptions

***Parsing functions must***

1. be stateless - depend only on input *string*
2. make decisions locally - return one result or fail

http://www.brynosaurus.com/pub/lang/peg-slides.pdf



one result could be success too!

## Parsing Expression Grammars

- A *PEG* $P = (\Sigma, N, R, e_S)$
  - —$\Sigma$ : a finite set of *terminals* (character set)
  - —N : finite set of *non-terminals*
  - —R : finite set of rules of the form "$A \leftarrow e$", where $A \in N$, and e is a *parsing expression*
  - —$e_S$ : the *start expression* (a parsing expression)

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

## Parsing Expressions

| | |
|---|---|
| $\varepsilon$ | the empty string |
| <u>**a**</u> | terminal (<u>**a**</u> $\in \Sigma$) |
| A | non-terminal ($A \in N$) |
| $e_1\ e_2$ | sequence |
| $e_1$ / $e_2$ | prioritized choice |
| $e^?$, $e^*$, $e^+$ | optional, zero-or-more, one-or-more |
| &e, !e | syntactic predicates |

http://www.brynosaurus.com/pub/lang/peg-slides.pdf



NB: "." is considered to match anything, so "!." matches the eof.

## How PEGs express languages

- Given an input string **s**, a parsing expression **e** either:
  - —Matches and consumes a prefix **s'** of **s**, or
  - —Fails on **s**

*S* ← **<u>bad</u>**

S matches "**<u>bad</u>der**"
S matches "**<u>bad</u>dest**"
S *fails* on "**abad**"
S *fails* on "**babe**"

## Prioritized choice with backtracking

$S \leftarrow A / B$

*means:* first try to parse an A.
If A fails, then backtrack and try to parse a B.

$S \leftarrow$ **if** C **then** S **else** S
/ **if** C **then** S

S matches "**if** C **then** S foo"
S matches "**if** C **then** $S_1$ **else** $S_2$"
S *fails* on "**if** C **else** S"

http://www.brynosaurus.com/pub/lang/peg-slides.pdf



NB: Note that if we reverse the order of the sub-expressions, then the second sub-expression will never be matched.

# Greedy option and repetition

| | | |
|---|---|---|
| $A \leftarrow e^?$ | *is equivalent to* | $A \leftarrow e \ / \ \varepsilon$ |
| $A \leftarrow e^*$ | *is equivalent to* | $A \leftarrow e \ A \ / \ \varepsilon$ |
| $A \leftarrow e^+$ | *is equivalent to* | $A \leftarrow e \ e^*$ |

$$\boxed{\begin{array}{l} I \leftarrow L^+ \\ L \leftarrow \underline{\mathbf{a}} \ / \ \underline{\mathbf{b}} \ / \ \underline{\mathbf{c}} \ / \ \ldots \end{array}}$$

I matches "**foobar**"
I *fails* on "**123**"

## Syntactic Predicates

&e succeeds whenever e does, *but consumes no input*

!e succeeds whenever e fails, *but consumes no input*

A ← **foo** &(**bar**)
B ← **foo** !(**bar**)

A matches “**foobar**”
A *fails* on “**foobie**”
B matches “**foobie**”
B *fails* on “**foobar**”

http://www.brynosaurus.com/pub/lang/peg-slides.pdf



&e introduced by Parr

## Example: nested comments

Comment ← Begin Internal* End
Internal ← !End ( Comment / Terminal )
Begin ← <u>/**</u>
End ← <u>*/</u>
Terminal ← [*any character*]

C matches "**<u>/**ab*/cd</u>**"
C matches "**<u>/**a/**b*/c*/</u>**"
C *fails* on "**/**a/**b*/**



Comment <- Begin iNternal* End

A comment starts with a begin marker.

Then there must be some internal stuff and an end marker.

The internal stuff must *not* start with an end marker.

Then it may be a nested comment or any terminal (single char).

# Formal properties of PEGs

> **Expresses all deterministic languages — LR(k)**
> **Closed under union, intersection, complement**
> **Expresses some non-context free languages**
—e.g., $\mathbf{a}^n\mathbf{b}^n\mathbf{c}^n$
> Undecidable whether $L(G) = \varnothing$

http://www.brynosaurus.com/pub/lang/peg-slides.pdf

## Roadmap

- > Domain Specific Languages
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- > **Packrat Parsers**
- > Parser Combinators

# Top-down parsing techniques

***Predictive parsers***

- use lookahead to decide which rule to trigger
- fast, linear time

***Backtracking parsers***

- try alternatives in order; backtrack on failure
- simpler, more expressive (possibly exponential time!)

# Example

Add ← Mul **+** Add / Mul
Mul ← Prim __*__ Mul / Prim
Prim ← **(** Add **)** / Dec
Dec ← **0** / **1** / … / **9**

```
public class SimpleParser {
  final String input;
  SimpleParser(String input) {
    this.input = input;
  }
  class Result {
    int num; // result calculated so far
    int pos; // input position parsed so far
    Result(int num, int pos) {
      this.num = num;
      this.pos = pos;
    }
  }
  class Fail extends Exception {
    Fail() { super() ; }
    Fail(String s) { super(s) ; }
  }
...
  protected Result add(int pos) throws Fail {
    try {
      Result lhs = this.mul(pos);
      Result op = this.eatChar('+', lhs.pos);
      Result rhs = this.add(op.pos);
      return new Result(lhs.num+rhs.num, rhs.pos);
    } catch(Fail ex) { }
    return this.mul(pos);
  }
...
```

***NB:*** *This is a scannerless parser — the terminals are all single characters.*



NB: Instead of using exceptions, we could encode failure in the Result instances.

Then instead of putting alternatives in try/catch blocks, we would have to test each result for failure.

Scannerless parsers are especially useful when mixing languages with different terminals.

# Parsing “6*(3+4)”

Add ← Mul **+** Add / Mul
Mul ← Prim ***** Mul / Prim
Prim ← **(** Add **)** / Dec
Dec ← **0** / **1** / … / **9**

```
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char 5
Char 6
Char *
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char *
Mul <- Prim [BACKTRACK]
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char +
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
```

```
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char 5
Char 6
Char *
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char *
Mul <- Prim [BACKTRACK]
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char +
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
```

```
[ ... ]
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char +
Add <- Mul [BACKTRACK]
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char *
Mul <- Prim [BACKTRACK]
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char )
Eof
312 steps
6*(3+4) -> 42
```

# Memoized parsing: Packrat Parsers

> Formally developed by Birman in 1970s

*By memoizing parsing results, we avoid having to recalculate partially successful parses.*

```
public class SimplePackrat extends SimpleParser {
  Hashtable<Integer,Result>[] hash;
  final int ADD = 0;
  final int MUL = 1;
  final int PRIM = 2;
  final int HASHES = 3;

  SimplePackrat (String input) {
    super(input);
    hash = new Hashtable[HASHES];
    for (int i=0; i<hash.length; i++) {
      hash[i] = new Hashtable<Integer,Result>();
    }
  }

  protected Result add(int pos) throws Fail {
    if (!hash[ADD].containsKey(pos)) {
      hash[ADD].put(pos, super.add(pos));
    }
    return hash[ADD].get(pos);
  }
...
}
```

# Memoized parsing “6*(3+4)”

```
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char 5
Char 6
Char *
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char *
Mul <- Prim [BACKTRACK]
PRIM -- retrieving hashed result
```

```
Char +
Add <- Mul + Add
Mul <- Prim * Mul
Prim <- ( Add )
Char (
Prim <- Dec [BACKTRACK]
Dec <- Num
Char 0
Char 1
Char 2
Char 3
Char 4
Char *
Mul <- Prim [BACKTRACK]
PRIM -- retrieving hashed result
Char +
Add <- Mul [BACKTRACK]
MUL -- retrieving hashed result
Char )
Char *
Mul <- Prim [BACKTRACK]
PRIM -- retrieving hashed result
Char +
Add <- Mul [BACKTRACK]
MUL -- retrieving hashed result
Eof
56 steps
6*(3+4) -> 42
```

# What is Packrat Parsing good for?

> Linear cost
—bounded by size(input) × #(parser rules)

> Recognizes strictly larger class of languages than deterministic parsing algorithms (LL(k), LR(k))

> Good for scannerless parsing
—fine-grained tokens, unlimited lookahead

http://www.brynosaurus.com/pub/lang/packrat-icfp02-slides.pdf



Cost – must cache at most # positions for each parser rule

# Scannerless Parsing

> Traditional linear-time parsers have fixed lookahead
  —With unlimited lookahead, don’t need separate lexical analysis!

> Scannerless parsing enables unified grammar for entire language
  —Can express grammars for mixed languages with different lexemes!

## What is Packrat Parsing *not* good for?

> General CFG parsing (ambiguous grammars)
>
> —produces at most one result

> Parsing highly “stateful” syntax (C, C++)
>
> —memoization depends on statelessness

> Parsing in minimal space
>
> —LL/LR parsers grow with stack depth, not input size

## Roadmap

> Domain Specific Languages
> Parsing Expression Grammars
> Packrat Parsers
> **Parser Combinators**

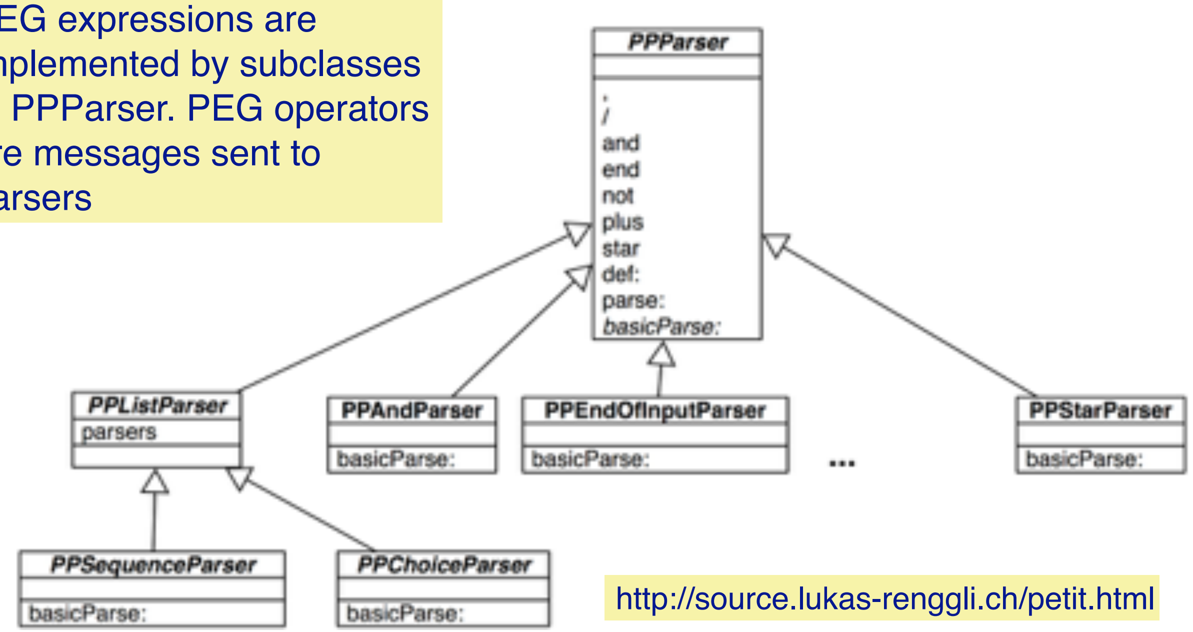
# Parser Combinators

> Parser combinators in **functional languages** are higher order functions used to build parsers
  - e.g., Parsec, Haskell

> In an **OO language**, a combinator is a (functional) object
  - To build a parser, you simply compose the combinators
  - Combinators can be reused, or specialized with new semantic actions
    - *compiler, pretty printer, syntax highlighter …*
  - e.g., PetitParser, Smalltalk

## PetitParser — a PEG parser combinator library for Smalltalk

PEG expressions are implemented by subclasses of PPParser. PEG operators are messages sent to parsers




http://source.lukas-renggli.ch/petit.html

# PetitParser example

```
| goal add mul prim dec |

dec := $0 - $9.
add := ( mul, $+ asParser, add )
       / mul.
mul := ( prim, $* asParser, mul)
       / prim.
prim := ( $( asParser, add, $) asParser)
       / dec.

goal := add end.
goal parse: '6*(3+4)' asParserStream
       ➔ #($6 $* #($( #($3 $+ $4) $)))
```

| | | |
|---|---|---|
| Add | ← | Mul + Add / Mul |
| Mul | ← | Prim * Mul / Prim |
| Prim | ← | ( Add ) / Dec |
| Dec | ← | 0 / 1 / … / 9 |

# Semantic actions in PetitParser

```
| goal add mul prim dec |

dec := ($0 - $9)
       ==> [ :token | token asNumber ].
add := ((mul , $+ asParser , add)
       ==> [ :nodes | nodes first + nodes third ])
       / mul.
mul := ((prim , $* asParser , mul)
       ==> [ :nodes | nodes first + nodes third ])
       / prim.
prim := (($( asParser , add , $) asParser)
       ==> [ :nodes | nodes second ])
       / dec.
goal := add end.

goal parse: '6*(3+4)' asParserStream ➔ 42
```

| | | |
|---|---|---|
| Add | ← | Mul + Add / Mul |
| Mul | ← | Prim * Mul / Prim |
| Prim | ← | ( Add ) / Dec |
| Dec | ← | 0 / 1 / … / 9 |

# Parser Combinator libraries

> Some OO parser combinator libraries:
>   - Java: JParsec
>   - C#: NParsec
>   - Ruby: Ruby Parsec
>   - Python: Pysec
>   - *and many more …*

# Jparsec — composing a parser from parts

```
public class Calculator {
   …
   static Parser<Double> calculator(Parser<Double> atom) {
      Parser.Reference<Double> ref = Parser.newReference();
      Parser<Double> unit = ref.lazy().between(term("("), term(")")).or(atom);
      Parser<Double> parser = new OperatorTable<Double>()
            .infixl(op("+", BinaryOperator.PLUS), 10)
            .infixl(op("-", BinaryOperator.MINUS), 10)
            .infixl(op("*", BinaryOperator.MUL).or(WHITESPACE_MUL), 20)
            .infixl(op("/", BinaryOperator.DIV), 20)
            .prefix(op("-", UnaryOperator.NEG), 30).build(unit);
      ref.set(parser);
      return parser;
   }

   public static final Parser<Double> CALCULATOR = calculator(NUMBER).from(
         TOKENIZER, IGNORED);
}
```

http://jparsec.codehaus.org/jparsec2+Tutorial

## *What you should know!*

- ✎ *Is a CFG a language recognizer or a language generator? What are the practical implications of this?*
- ✎ *How are PEGs defined?*
- ✎ *How do PEGs differ from CFGs?*
- ✎ *What problem do PEGs solve?*
- ✎ *How does memoization aid backtracking parsers?*
- ✎ *What are scannerless parsers? What are they good for?*
- ✎ *How can parser combinators be implemented as objects?*

## Can you answer these questions?

- ✎ Why is it critical for PEGs that parsing functions be stateless?
- ✎ Why do PEG parsers have unlimited lookahead?
- ✎ Why are PEGs and packrat parsers well suited to functional programming languages?
- ✎ What kinds of languages are scannerless parsers good for? When are they inappropriate?